THE FUNDAMENTALS OF SEACOAST JETTIES

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THE FUNDAMENTALS OF SEACOAST JETTIES

THE ENGINEER SCHOOL
FORT HUMPHREYS, VIRGINIA
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THE FUNDAMENTALS OF SEACOAST JETTIES

In American practice the term "Jetty" is applied to a structure built at the entrance to a harbor or at the mouth of a river to confine and direct the currents so as to maintain a navigable channel and to protect such channel from sand movement which would cause deterioration. The two main classes of jettied entrance channels, involving somewhat different methods of treatment, are those in which river discharge is the principal agent in causing scour and those in which the chief dependence is placed upon tidal flow. These two classes naturally merge, as we rarely find a harbor into which at least one stream of some size does not discharge. However, in nearly every case either river discharge or tidal flow is greatly predominant. In this country tidal flow is the factor of major importance in practically all of our jetty problems and this class will be given the greater attention in the following pages. The mouths of the Mississippi furnish an outstanding example of the other class.

The harbor engineer faces his greatest problem in the creation and maintenance of a suitable channel across the bar ordinarily found at the entrance. To be sure he is limited to a choice between dredging and jetty construction or to a combination of the two. But the selection of the exact method and its adaption to the particular site involves the nicest discrimination coupled with the application of experience and judgement after a deep study of all ascertainable data relative to the location. The forces which have built up the bar in the past and which will affect the proper maintenance of the bar channel are difficult, if not impossible, of exact determination. They are intermittent and vary greatly in direction, intensity and duration. They may even be modified by the changed conditions set up by the new improvement. But the effect of these forces must be gauged accurately, and some of them must be guided and utilied, if the improvement is to be a success.

A full measure of success is especially desirable in the entrance channel as so much depends upon it. Bar work is always costly. If it be not effective there is a heavy direct loss from the non-productive expenditures on the bar itself, but not infrequently an even greater loss may result from the impaired value of the inner harbor

improvements. Realization on the investments made on these inner works together with the prosperity of a considerable section of the country, will frequently be dependent upon ready and constant access to the sea. On the other hand a dependable channel cannot be the sole criterion Relative costs must also be given full weight. No such project can be considered entirely successful if a materially cheaper plan would have accomplished the desired results. The engineer must thus investigate conditions with the utmost care and study his data from all angles before deciding upon the details of his entrance channel project.

General Remarks on Channel Location. The more important natural phenomena and engineering principles affecting the siting of channels across ocean bars will be brought out hereafter. It is desired, however, at the outset to give all possible emphasis to one fundamental principle. It must be remembered that *the channel is being created to meet the needs of navigation.* No plan which does not adequately fulfill this requirement may be considered merely because it is easier or cheaper to construct.

On account of the great cost of jetty construction there will often be a temptation to try partial measures in the hope that, through some fortuitous circumstance, the expense may be reduced. The result is almost certain to be an ultimate increased cost in completing an adequate improvement. In the interim shipping will have had an unsatisfactory and costly experience. So much depends upon entire success in this work that the engineer must keep constantly before his mind the fact that his aim is a dependable channel, safe and suitable for the use of shipping at all seasons and in all sorts of weather.

The design must be predicated upon the worst conditions. Vessels using the entrance during storms must find a channel of suitable width and proper direction, easy to enter and to follow. It is essential that they be not required to move along a lee shore in making or leaving the entrance and that they have either a following or a head sea while traversing the channel. Exposure to a beam sea in a narrow channel is apt to lead to disaster. Those very practical navigation requirements fix the direction of the channel as essentially that of the prevailing heavy storms. Local conditions may cause some slight deviation from this line and may dictate absolutely the location of controlling works but any material departure from this fundamental rule is an invitation to trouble, under any but the most exceptional conditions.

SAND MOVEMENT

As a first step in the consideration of jetty systems and their action it is necessary to study the movement of sand on the seacoast. It is this movement which is primarily responsible for the formation of the obstructive bar and for the deterioration of bar channels.

In all but the very calmest weather the ocean is steadily attacking its shores. The waves, breaking on the beach, stir up the material of which it is composed, roll the particles over each other and grind them ever smaller and smaller, thus making them the more readily transportable. When the waves are breaking perpendicular to the beach the crest of each runs up the slope until its energy is exhausted. This water then flows back down the slope, its velocity constantly increasing until it is met by the next succeeding wave, which it underruns with decreasing velocity until finally stopped. It is evident that this motion of the waves, repeated over and over again with monotonous regularity, will tend to scour the section of the beach on which it acts. Some particles will be carried farther up the beach by the incoming wave and there dropped as the energy of the water is dissipated. Much of the material moved up the slope by the breaker will be carried back seaward by the return water which will also pick up additional material from the beach as its velocity increases. All this will be deposited toward the foot of the slope as the flow is checked by the succeding wave. As the amplitude of the waves or the level of the water surface changes a different stratum of the beach is subjected to this action. The part formerly eroded will be filled up again while cutting goes on at the new level. As this motion is perpendicular to the slope of the beach there is no tendency to a translation of the material along-shore, unless the undertow carries some of the finer particles far enough seaward to bring them under the influence of currents which will move it laterally. The sole effect of the action described is to reduce the size of the materials composing the beach and thus to render them the more susceptible to movement by the waves.

If, instead of approaching the shore at right angles, the waves break obliquely, we see a different result. In modification of the action just outlined there will be a progressive movement of the beach material alongshore in the direction of the component of the waves' travel parallel to the coast. The particles are driven diagonally up the beach by the incoming breaker instead of perpendicularly as before. As the wave loses its force and the water flows

back down the slope, the material moves with it, only to be picked up and moved forward once more by the next wave. The individual particles thus advance along the beach cumulative effect being an extensive sand movement. During heavy blows the amount of sand in motion is enormous as the waves agitate material from the ocean bottom not affected by the ordinary seas. On the North Pacific coast storm waves have been known to disturb the heavy sand bottom in depths upward of 100 feet. There is usually sufficient inclination of wave to shore so that some sand movement is the normal condition.

Effect of Currents. When the wave-forming winds continue to blow from the same general direction at an angle with the coast for considerable periods of time, an alongshore current is set up by the components of the waves acting in that direction. The intensity of these currents and the extent of their effect are functions of the coastal topography and the force, direction and continuity of the wind. Normally rather weak, they sometimes become of very appreciable strength under the influence of a long-continued heavy blow. These currents, produced directly by the action of the wind formed waves striking the shore obliquely and moving close inshore, are the true "littoral currents," and that term, often loosely applied to many forms of alongshore currents, should be reserved for them.

The littoral currents, acting in conjunction with the attack of the waves upon the coast, have a great effect upon the general sand movement. Though rarely, if ever, sufficiently strong to erode the bottom themselves, they can and do act upon the material which is stirred up by wave action. The lighter material is frequently transported for long distances in suspension, while the heavier particles are moved along the shore steadily, if more slowly and with frequent stops until again stirred up by the waves.

It is doubtful if there is any point on the coast of the United States where the main ocean currents or any of their eddies affect materially the movement of sand. Tidal currents, on the other hand, do have a decided effect under certain circumstances. On the open coast these currents have not sufficient force to move material unaided. When there is wave action to stir up the sand, however, they are often capable of moving the dislodged particles in much the same manner as the true wave formed littoral currents. But we have seen that, except in the unusual and rarely prolonged case of waves acting perpendicular to the shore, wave action regularly produces these littoral currents. Thus the principal effect

of tidal currents is to retard or intensify the true littoral currents, depending upon their respective directions, and correspondingly to decrease or increase the amount of current-borne sand.

In the immediate vicinity of inlets and entrances to harbors the character and action of tidal currents change appreciably. The currents in such localities become concentrated and much stronger than along the open coast. Under such conditions they have a vastly greater sand-moving power. Their action will be touched upon in more detail later.

Littoral Drift. The movement of sand along the shore under the combined action of waves and currents as outlined above is referred to as "littoral drift." It is obvious that the drift is far from constant in either direction or amount, as the winds, which are primarily the controlling factors, vary in strength from gentle breezes to heavy gales and blow from all points of the compass at different times. There is invariably, however, a seasonal prevailing wind, with a corresponding seasonal prevailing drift. As a rule, the prevailing drift during the summer is opposite to that during the winter and the relation between the two varies from year to year. But in practically every case the drift in one direction is regularly greater than in the other so that the direction of the resultant drift is constant. This resultant annual littoral drift is frequently referred to as the "prevailing drift," and sometimes merely as the "littoral drift," disregarding the movement in the opposite direction. It is essential, however that this sand movement in the direction opposite to the prevailing drift be taken into consideration in the design of a jetty system. It is frequently very extensive and only becomes minor when compared to the greater amount in the prevailing direction.

The determination of the direction of the prevailing is not always an easy matter. It must be remembered that the prevailing drift will not necessarily follow the prevailing wind when direction alone is considered. Both intensity and duration of the winds are vital factors in the equation. It frequently happens that the heaviest storms come from an entirely different quarter than the more prolonged lighter breezes. As the high-rolling storm waves are much the more effective in producing sand movement, the result of one storm may more than counteract the effect of continued light winds of several weeks duration. On the other hand the action of the prolonged lighter winds must not be unduly discounted. Their cumulative effect is often controlling. For instance, on the North Pacific coast the winds blows from the northwest many more days each year than from any other quadrant, as

the summer trade winds are almost invariable for months. The hardest summer gales also come from the same direction. But these summer storms by no means equal in severity or frequency the storms of the winter season. The winter storms commence usually in the southwest, veering through the south with increasing violence until they reach their maximum intensity in the southwest and dying out as they swing farther to the west. These storms not infrequently last for several days and occasionally follow each other in rapid succession, always blowing hardest while in the southwest squadron. The resulting sand movement to the north is tremendous but the steady, gentle drift to the south for the greater part of the year counterbalances the more spectacular storm action, giving an annual resultant southerly motion.

The ground swell is another factor which should be taken into account. This is a wave, frequently of great force, which is created by storms far off shore and is propogated to great distances as a long wave of considerable depth. It is entirely independent of local winds but frequently is very effective in stirring up sand from the bottom.

Its prevalence, usual direction and intensity at any point can only be determined by observation and consultation with reliable residents as records will usually be silent in this regard.

The terms "windward" and "leeward," as used in jetty parlance, refer to the prevailing drift, i.e. the annual resultant movement, rather than to the wind itself. As so used, windward is toward the direction from which the prevailing drift comes.

One other sand-moving agency should doubtless be mentioned here, although it is of minor importance as regards the subject of jetties. At many points on the seacoast the wind moves large quantities of sand directly, without the interposition of wave action. The heavier storm waves throw part of the material they are moving far up the beach beyond the level ordinarily reached by the seas. This material, upon drying out, is picked up by the wind and its movement thereafter is dependent upon the character of the material itself and the direction and intensity of the winds. Sometimes it will be carried as a cloud of rapidly moving particles, traveling for miles under the influence of one blow. Again it will be formed into dunes, which advance slowly and inexorably, covering everything in their path. The subject of wind-driven sand and its control—a very important and interesting one—cannot be gone into here. It is worthy of separate treatment. The ordinary jetty structure cannot be expected to exert any material influence upon this type of sand movement.

Bar Formation. At the entrance to practically every harbor on a sandy coast we find a bar, usually crescent shaped and convex to the sea, although this is far from invariable. This bar represents the resultant of the various forces acting upon the sand at the entrance. When the material being moved along the coast under the influence of the littoral drift reaches an entrance it is carried toward the harbor by the flood current and seaward by the ebb. There is a natural tendency for these tidal currents to concentrate and form a comparatively narrow swift-moving stream. This tendency is particularly noticeable on the ebb. The result of this concentration is the formation of a deep gorge just within the entrance. The presence of this gorge, in its turn, assists in keeping the tidal current concentrated.

As the water moves seaward on the ebb tide it passes through the gorge at a relatively high velocity. Upon leaving the gorge part of the flow spreads out fan shape, gradually losing velocity and, of course, dropping any material it may be carrying. This naturally results in the formation of a shoal. The shape which this shoal assumes depends upon the relative strength of the tidal and litoral currents. Sediment carried by an interior streams in flood, material moving along the coast and sand dislodged from the bottom of the sea and pushed shoreward by storms add to the bar, while the ebb tides prevent it growing so high as to interfere with tidal flow. There is thus a constant alternation between growth and erosion.

Bar Channels. Although, as has been seen, a part of the main ebb flow spreads out after leaving the gorge, there still remains a strong tidal stream which does not entirely lose its cohesion and identity until it has crossed the crest of the bar. This more concentrated flow, with its greater erosive power, tends to create deeper water on the portion of the bar against which it impinges than is found elsewhere. There is thus usually a natural channel of sorts across every bar. The flood tide tends to concentrate in this deeper channel, thus also assisting in its maintenance. As a rule, however, this channel is of insufficient depth and too unstable in location to be satisfactory for modern navigation. It is exceptional for the natural bar channel to remain fixed in position over long periods of time. Sometimes it shifts about erratically, following no apparent rule but evidently moving in accordance with local and temporary eccentricities in the forces acting upon it. Frequently, however, the position of the channel changes with comparative regularity, moving fairly steadily across the bar to the leeward, then

breaking out on the windward side once more. A brief consideration of the factors affecting this movement will show the reasons for its cyclical character.

The littoral drift tends to narrow the channel by depositing sand on the windward side. Tidal ebb and flow resist this narrowing action by scour on the sides of the channel to maintain the normal width. This tidal erosion will normally be about equal on the two sides. Necessarily as this process continues the channel moves across the bar in the direction of the littoral drift. We have seen that the drift is not constant in direction. Correspondingly the channel does not move steadily. At times it will remain practically stationary for a considerable period and again it will move in the opposite direction for a time as the drift changes. In the long run, however, there is a decided movement in the direction of the prevailing drift.

There is no corresponding influence to move the position of the gorge within the throat of the harbor, so it remains essentially unchanged. The ebb currents leaving the gorge thus have an over lengthening route to the sea as the bar channel shifts farther leeward. This longer path which the currents must follow means a flatter slope, less ready discharge for the water and a consequent heavier pressure on the enclosing bar which has built up on the outside of the diverted currents. Eventually the increased strain on the outer sand spit becomes sufficiently great to enable the currents to scour a direct outlet to the sea once more. Sometimes this "breakout," as it is called, occurs suddenly under the added impulse of a favoring storm or of a flood in a river tributary to the harbor. More frequently, however, it is a gradual process, the new channel increasing in size while the old one fills up. While this change is under way the channel conditions on the bar are usually at their worst, as there are two and occasionally even three partial channels with no good one. On the other hand, when the breakout is finally completed and the new conditions firmly established, preparatory to the beginning of a fresh cycle, we find the channel deepest and most suitable for navigation. It appears to be the general rule that the farther to windward the breakout occurs the better will be the resulting channel and the longer will it maintain itself. The probable explanation of this will appear later.

It is impossible to determine far in advance just where, or even when, a breakout will occur under natural conditions. In most cases a complete cycle requires many years, harbors differing greatly in this respect due to varying local conditions. But often the cycle is interrupted by some abnormal condition causing a breakout

before the channel has attained its extreme leeward position. Such secondary breakouts may occur more than once during a complete cycle. Even when the channel has shifted to its extreme leeward position the breakout may not be far to the windward side of the bar. It, of course, appears logical that the most probable position for a breakout should be directly in front of the gorge, where the currents find the most direct path to the sea and should exert their greatest effect. But the bars are not of equal strength throughout nor is their structure always homogeneous. The new channel will then be cut through the bar at the weakest point, which may be some distance from the windward side. In fact it is exceptional that anything like the theoretical cycle of a steady swing from windward to leeward followed by a breakout in the original position and a repetition of the process will be experienced in practice. The tendency is always in that direction, however, and it is well to understand it.

BAR CHANNEL LOCATION

The forgoing discussion of sand movement, while far from exhaustive, is sufficient for our purposes in this study. We will next turn to a consideration of the best location for the proposed artificial channel across the bar. It is axiomatic that, from the viewpoint of ultimate economy and dependability, the most favorable position of the channel is the one least subject to impairment from the forces acting upon it. The great cause of bar channel deterioration is moving sand. Consequently the effort should be to locate the channel in such manner as to reduce to a minimum the effect of the sand movement. This applies equally to jettied channels and to those created and maintained by dredging alone.

It has been shown that the effect of the littoral drift is to deposit sand on one side of the channel, thus gradually pushing it across the bar to leeward. No mere siting of the channel can prevent this action. Without protective works to catch and hold the littoral drift, the channel will tend to shift and there must be resort to periodic dredging to hold it in place. But littoral drift is not the only sand movement affecting channel maintenance and it is possible to guard against the other major influence, i.e. storm waves.

We know that heavy storms, with their accompanying waves of great depth, stir up the sand on the bottom of the ocean and move it shoreward. This sand is driven directly before the waves until it reaches the shore, where it joins the littoral drift. The forces behind its movement are to great to permit any material deflection in its direction under the influence of shore currents. If, then, the

bar channel has its axis perpendicular to the storm waves, the tendency for sand to be driven into it from either side will be reduced to a minimum. This condition is most desirable, as a uniform deposit of material across the cut presents the best opportunity for the scouring action of the tidal currents to hold the channel in place. Of course the winds that are sufficiently strong to stir up and transport the sand do not all come from the same direction. We know, however, that there is usually one direction from which such winds blow more frequently than from any other. The foregoing considerations obviously point to the tentative selection of a line into the face of the prevailing storms for the channel axis.

Thus far the direction of the waves has been considered as identical with that of the winds forming them. In the deep water of the open sea this is literally true. As the waves enter the shallower water near the shore at an angle with the coast line, however, there is a tendency for the inshore end of the wave to lag, the wave crest thus becoming more nearly parallel to the shore. In some localities the shape of the ocean bottom, the position of nearby headlands or other local physical characteristics accentuate this tendency so that the waves reach the shore at an appreciable angle with the direction of the wind. It is, of course, the waves, rather than the winds creating them, that actually cause sand movement. Thus the location should really be based on the prevailing direction of the waves. Each locality must be studied with care to determine just how material such deviation of wave direction from wind direction may be at that particular point. The prevalence and relative importance of the ground swells previously referred to should also be considered. In the exceptional case it may be necessary to take into account some extraordinary local current. After full consideration of all such modifying factors it will frequently prove desirable to shift somewhat the direction of the channel axis from that tentatively selected, in order that the location finally decided upon may be as little subject to deterioration as possible.

In the usual case the indicated desirable change in the bearing of the channel axis will not vary much more than a few degrees from the direction of the prevailing blows. This is the more fortunate in that such a direction is the best in the interests of easy navigation as was pointed out above. When we encounter the abnormal situation of waves advancing at a decided angle with the wind, indicating the propriety of making a corresponding change in the channel axis, the suitability of such a modified alignment for navigation must be studied with great care. In such case, the easiest course for navigators to follow will be one between the di-

rection of the wind and that of the waves, in order that neither force may take the vessels abeam. Here a compromise location will be necessary but in every case the navigation viewpoint must be paramount.

Turning now to the question of the exact location of the channel on the bar the problem is simple. From every viewpoint, ease and economy of construction and maintenance, ready ingress and egress of tidal flow and maximum scouring effect of the tidal currents, the most direct line across the bar is the best. Given the direction of the channel axis, it is evident that the shortest distance across the bar is at the point where such line is at right angles to the crest. Very rarely will any local conditions be found which will militate against such a location.

Based upon the foregoing discussion we may state a general rule that a bar channel may usually be best sited with its axis in the direction of the prevailing heavy blows, modified as may be necessary to meet local conditons, at that point on the bar where such axis line is perpendicular to the crest.

Experience indicates that this theoretically correct location for the bar channel proves itself in practice. In some cases where the channel has not been given the stated direction in the first instance, it has gradually shifted until its axis had the bearing it should have been given at first. The most windwardly position of the natural channel as it moves in its cycles, and which was stated above to have the best depth and the longest life, usually corresponds very closely to the description given. This doubtless accounts for its observed excellence.

JETTY DESIGN

If a properly located channel of considerable capacity is formed across a bar by dredging or otherwise, there is a natural tendency for the tidal flow to concentrate in such channel. This concentration of flow, with its accompanying increased velocity and volume, tends to produce scour in the channel, increasing its depth and carrying capacity. There is a corresponding tendency for the reduction of flow over the rest of the bar to induce increased deposit of material outside the channel. Were there no other forces at work to counteract these effects, there should result eventually a deep, relatively narrow bar channel, through which essentially the entire tidal flow would take place. The dimensions of the channel would be dependent upon the tidal volume and the angle of repose of the material forming the bar. Outside of the channel the bar would be high and wide, with practically no flow over it.

But this very desirable condition is far from the true state of affairs, as we know. In fact there are constantly exerted strong forces tending to close the channel and to shift it from its position, so that the tides have a never-ending struggle to maintain the flowage space that they need. The purpose of a jetty system is really to produce by artificial means the results outlined above, through concentrating and aiding the currents which keep the channel open, while opposing as far as practicable those forces tending toward its deterioration.

Every successful jetty system must thus serve a dual purpose. First, the jetties must concentrate the ebb currents at the proper point on the bar and in the proper direction so as to secure the maximum benefit from their scouring action. Second, they must act as sand fences to catch and hold the littoral drift, at least until the new channel is firmly established. Both of these functions are essential and no jetty system can be successful if either requirement is not adequately met. Experience has shown conclusively that to fulfill these requirements satisfactorily two jetties are necessary. Frequently a single jetty will produce satisfactory channel for a time—sometimes for several years. But invariably the promise of a permanent improvement is not fulfilled and eventually the second jetty must be built, often at a greatly increased cost. The reasons for this are apparent upon a brief consideration of the factors involved.

Single Windward Jetty. The construction of a single jetty to the windward of the bar channel will usually result in a marked, though temporary, improvement in channel conditions. The jetty catches and holds much of the sand moving in the direction of the prevailing littoral drift. The ebb currents, relieved of the burden of caring for this sand, exert their scouring power more effectively. There is thus a two-fold influence tending toward a betterment of the channel, i.e. protection from the drifting sand and increased effectiveness of scour. The beneficial results are quickly apparent and a satisfactory channel is formed.

Favorable local conditions may permit this improved channel to endure for an extended period but other forces, tending to destroy the good so far done, start their work at once. Although the littoral sand movement is arrested by the jetty, the forces which bring this movement about are still acting on the bar to leeward of the channel The waves stir up the material of which the bar is composed and their alongshore component starts it moving in the direction of the littoral drift. As no new material is being added from the windward, the bar begins to grow smaller and its crest

to become lower. This effect in turn relieves the constraint on the ebb flow, allowing it to escape more freely over the entire bar. The currents are no longer held firmly to their work of scouring in the main channel. Of course, when the littoral drift undergoes its seasonal change and begins acting against the prevailing direction, the bar will build up again for the time being. In the long run, however, the same causes which produce a prevailing direction of the littoral drift will bring about an ultimate, if gradual, degradation of the bar. The resultant lessening in the concentration of ebb currents will be followed by a deterioration of the channel.

It must not be supposed that the construction of the jetty has entirely prevented the introduction of sand into the channel. There is always a certain leakage of material through and around the jetty. When the sea is rough enough to stir up the bottom every flood tide brings in sand. Frequently rivers discharging into the estuary bring down quantities of material, while the changed conditions on the bar bring about changes of currents within the harbor which cause erosion and provide more sand to be moved seaward. Rarely do all of these causes combined produce any trouble as long as the ebb currents are held to their work against the jetty. But when the degradation of the bar has proceeded sufficiently for that the ebb has more freedom, sand may begin to be deposited between the channel and the jetty and even in the channel itself, reducing its depth. The stage is now set for the final act in the return of the channel to its original unsatisfactory condition.

The area to windward of the jetty has not an unlimited capacity for the storage of sand. Eventually the littoral drift will fill it up. As the storage capacity nears exhaustion sand will begin ot work around the end of the jetty in increasing quantities. The no longer concentrated ebb flow is unable to deal with this additional deposit. The channel leaves the jetty and begins once more to wander across the bar. The only result which the jetty has accomplished is possibly to reduce the swing of the channel, as it is now restricted to the distance between the end of the jetty and the lee shore. Even this is more apparent than real as the jetty will doubtless not be sited far from the most windwardly position of the channel under natural conditions.

On casual consideration it may appear that at least the construction of the jetty has reduced the length of bar over which the ebb may spill, has thus forced a material concentration of flow and that accordingly the channel even though it be not fixed in position will be more capacious than under natural conditions. Unfortunately the concentration that has been effected is not of the main

ebb flow, to which the natural channel is adjusted reasonably well, but merely of the minor escape over the crest of the bar. Its effect is insignificant in practice.

An excellent example of the temporary benefit to be obtained through the construction of a single jetty and the eventual need for two is found in the history of the improvement at the mouth of the Columbia River. A brief description of the effect of the various steps in this project follows. The first plan for the improvement of this entrance by jetty construction, adopted in 1882, contemplated a single jetty four and one half miles long on the south side of the channel. It was desired to secure a channel depth of 30 feet, natural depths having been as little as 15 feet, occasionally being as great as 25 feet under exceptionally favorable conditions, and probably averaging about 18 to 19 feet. Construction proceeded slowly, due to the meagre provision of funds, and the jetty was not completed until 1896. A favorable effect upon the channel was noticeable very soon after the structure had been pushed out from the shore. The channel became fixed in position and began to deepen. When work was stopped in 1896 there was a depth of 31 feet at mean low water across the bar.

But construction had gone ahead so slowly that the area south of the jetty had filled up with sand almost as fast as extension provided additional storage space. Consequently the sand drift began to move past the jetty almost immediately after its completion, whereupon the channel began to show a tendency to move to the north. By 1898 the channel had shoaled to 28 feet and had shifted nortward to an unstable location. Four years later the channel had divided, the best depth being but 21 feet. By this time a new project had been adopted. This called for a depth of 40 feet to be secured by the extension of the south jetty for two and one half miles and the later construction of a north jetty of the same length, the outer ends of the two jetties to be two miles apart. The south jetty extension was carried out first, work being started in 1903 and completed in 1913. As the south jetty was extended there was a gradual improvement in channel depths until by 1911 a depth of 27 feet was available. Thereafter there was no increase in depth but rather an apparent tendency toward shoaling. The north jetty was started late in 1913 and completed in 1918. By the summer of 1917 the channel depth was 41 feet. Since that time there has been a gradual increase in both depth and width of the channel, which has remained fixed in position. The examination in May, 1928, showed a channel with the project depth of 40 feet 7,000 feet wide, while a least depth of 46 feet was available over a width of 2500 feet.

We here see clearly the little good which was done by a single jetty at a point which became one of the outstanding examples of successful improvement by jetties as soon as the second jetty was built and the currents held up to their work.

Single Lee Jetty. The employment of a single jetty to leeward of the channel is based upon an entirely different theory but one which can be explained very briefly. The idea in this case is that the sand drift will force the channel against the jetty, which will hold it in place. The greater the sand movement and the longer it continues, the more will the tidal flow be concentrated and consequently the more powerful will be its scouring effect. The channel cannot be closed off as the tidal flow must have sufficient room to get in and out. So we have a very simple automatic and self-regulating device for channel construction and maintenance.

In fact the construction of a lee jetty is invariably followed by the formation of a satisfactory channel. Unfortunately the very forces which produce the channel sooner or later ruin it. A little thought will show that this must be so. Except for the period of reversed littoral drift, sand is being constantly moved toward and into the channel, only to be picked up and removed by the tidal currents. Quantities of sand are thus steadily carried seaward. As the heavily laden ebb currents are frequently worked to the limit of their capacities, they cannot carry much of this material beyond the point where they are held firmly to the narrow channel. Accordingly they begin to drop their load as soon as the end of the jetty is reached, where the sand goes to build out the sea face of the bar. More is deposited on the ocean floor just in front of the entrance, starting the seaward extension of the old bar or the formation of a new one.

Inevitably the result of this process is that a sand spit begins to build out from the bar, working around the end of the jetty and masking the entrance. As this spit is extended farther and farther across the end of the jetty, the flow of the ebb tide becomes seriously impeded. Eventually a breakout will occur either across the new sand spit or the old bar and we are back once more to the cyclic channel change of the natural bar conditions. No real improvement has been accomplished.

During the time that the sand spit is masking the entrance a serious problem faces navigation. A vessel entering the harbor must head toward the shore, turn abruptly around the end of the spit, run along its shore side until the end of the jetty is passed and then make another abrupt turn into the narrow channel alongside the jetty. Such a maneuver is difficult and dangerous under the

best of conditions and unthinkable when there is a gale or a heavy sea is running. Even when the channel runs straight to sea the narrow channel with a lee jetty close alongside is not attractive from the standpoint of a vessel passing through it, especially in stormy weather.

The Reaction Breakwater. The discussion of single jetties would not be complete without some reference to the detached jetty to which the name of "reaction breakwater" has been applied by its proposers. Space will not permit a full analysis of this structure but a brief consideration of its principles seems desirable. Essentially, the reaction breakwater is a single jetty, entirely detached from the shore, sited on the bar to the windward side of the channel and given a curved trace concave to the main ebb current. The claims of its proponents are that the section of jetty on the bar will act like the ordinary windward jetty in arresting the littoral drift, while the gap between the structure and the shore will admit the flood more readily; that the curved trace, acting in the same manner as the concave bends of a river, will give more adequate control of the ebb currents, producing a reaction across the bar and giving the effect of the ebb a marked advantage over the flood.

The cost of such a structure would, of course, be appreciably less than that of the two-jetty system, or even of the usual type of single windward jetty on account of the elimination of the shoreward portion. On no other count than cost does a critical analysis give the reaction breakwater any claim to favor. The sand storage behind the detached section of jetty would be indefinitely less than where a solid connection is made to the shore. Much of the sand drift is along the shore. This sand will pass through the gap between the jetty and the shore, getting into the channel and forcing it to the leeward. The gap is not really needed for the stated purpose of admitting the flood tide. Careful observations in numerous harbors with jettied entrances have failed to show any material reduction of gage heights or volume of the tidal prism after the improvement. There does not appear to be any other advantage in leaving the proposed gap which would in any degree compensate for the troubles to be expected from the free admission of the littoral drift into the inner end of the channel. If the gap were to be omitted and the structure built solid from the shore, we would have the ordinary windward jetty except for the curved trace on the bar, concave to the channel. This curvature is introduced for the purpose of securing the increased scouring effect from the ebb currents which always accompanies the flow of water in a curvilinear path. But consideration of the helicoidal theory of the flow of

water and of the observed results of such flow indicates that this action is not desirable here. When water is made to follow a curved path, the centrifugal force generated induces scour at the base of the directing obstacle, tending to undermine it, and results in a deep narrow channel close to the obstruction. As soon as the curve is passed and the heliocoidal flow straightens out, the additional load of sediment is deposited in a bar just beyond the curve. All of these effects should be avoided in a jettied bar channel.

From the foregoing it appears that the reaction breakwater has little of value to offer in the solution of the jetty problem. A detached jetty embodying the principles of the reaction breakwater was built at Aransas Pass, Texas, some thirty years ago. The results were far from satisfactory. Finally the improvement was completed by the adoption of the twin jetty principle and the reaction breakwater has not since been tried so far as is known.

Twin Jetties. The outline of causes and effects heretofore given shows that every consideration points to the necessity for the construction of two jetties to insure permanent results in the improvement of a bar channel. From the very nature and normal action of the forces causing the formation of bars and preventing the maintenance of satisfactory natural channels, it is obvious that there must be a material modification of natural conditions to insure a stable artificial channel. Not only must the sand movement be arrested and controlled, but the scouring action of the ebb currents must be strengthened and properly directed. A single jetty performs but a partial service. No such structure can be expected to do all that is required from a complete jetty system. To secure the full effect of the ebb tide scour, the currents must be held firmly to their work. This involves more control and more contraction than can be obtained without the use of two jetties. The experience of the Corps of Engineers on many jetty projects built under a great diversity of conditions has demonstrated quite clearly that this conclusion is correct. Under most exceptional circumstances, local conditions may hold out promise of success from a single jetty. Again the funds that can be made immediately available for construction may limit the project to one jetty for the time being. In the latter case, though, there is no justification for building the single jetty unless the commercial possibilities of the harbor will eventually warrant the expenditure involved in a twin jetty project. Whatever may be the reason for the initial construction of but one jetty, it should always be so sited as to fit into a twin jetty scheme. Otherwise it may prove impossible to design the final system in the

most efficient manner if, as is highly probable, it eventually becomes necessary to build a second jetty.

Design of Twin Jetty System Contraction. The location and direction of the bar channel having been decided upon in accordance with the principles heretofore enunciated, possibly the most important single point for determination in the design of a jetty system is the proper distance to be left between the outer ends. The contraction must be sufficient to produce currents capable of causing the requisite scour and to prevent shoaling or the formation of more than one channel between the jetties. On the other hand over-contraction must be avoided as it may be accompanied with serious ill effects. While experience has shown that a properly designed jetty system will not reduce the amplitude of the tidal variation within the harbor, too great a contraction at the entrance may actually lower the water level through retarding the tidal flow. Even though this extreme be not reached there will be excessive velocities across the bar. It might appear that excess velocity of the tidal current, with the accompanying increased scourin power, would not be particularly objectionable, provided it were not so great as to interfere with navigation, as it would merely result in greater depth of channel than was needed or contemplated. In fact, however, such a condition may seriously threaten the ultimate success of the improvement, if it be very marked.

It must be remembered that the concentrated currents, in scouring the channel across the bar, must move seaward great quantities of sand. This naturally tends to extend the bar farther out and so lengthen the path over which the scour must be effective if the channel is to be maintained in satisfactory condition. This tendency to push the bar seaward is the greatest objection to improvement by jetties. With a properly designed system it is possible to counteract this objectionable feature, as will appear later. Excessive scour, however, adds enormously to the amount of sand moved to the outer edge of the bar and to the difficulties of maintaining the channel through the bar extension. Eventually the jetty structures themselves may be undermined and destroyed, or such result only averted by expensive repair and protective measures. Under contraction can be corrected with comparative ease and at no prohibitive cost by additional construction. Over-contraction, on the other hand, is almost certain to lead to great difficulty and heavy expense. It is obvious that any uncertainties that may exist in the determination of the distance between the end of the jetties should be settled on the side of ample width of entrance.

Each harbor presents a distinct problem with conditions so different from those found at any other as to give generalizations no value. Similarly at any particular harbor the forces are so variable that an exact mathematical determination of proper width of entrance to fit all conditions is impossible. However, the problem of proportioning the width to the average condition, while complicated, is far from hopeless. The major factors are the area of the interior waters, the range of tide, the volume of water carried by streams flowing into the harbor and the character of the material forming the bar. The basic figure is the volume of the tidal prism. It is obvious that this quantity of water, augmented by the flow of any interior streams, must pass out through the entrance during the ebb. The volume of the tidal prism, of course, is merely the product of the tidal range and the effective area of the interior waters. The range of tide may be ascertained with great exactness, frequently from existing records. In the usual case it is rather difficult to determine exactly the effective area on account of irregularity of outline, variations in cross section, the numerous tidal sloughs so frequently found in the inner sections of bays, and similar factors complicating the situation. Of course it is possible to overcome these difficulties by means of an accurate survey made especially for the purpose but the expense of such a survey is not justified. Ordinarily existing maps, or, if none are available, a rough survey, coupled with a number of typical cross sections will answer all the necessary purposes for a reasonably close approximation of the tidal volume. It must be recognized throughout that in the very nature of the problem extreme refinement of processes is not warranted.

To the computed volume of the tidal prism there should be added the flow of tributary streams during the period of the ebb tide, where this amount is material. In many cases the flow of such streams will be so small when compared with the true tidal flow as well within the limit of probable error in the tidal volume determination. In such case they may be disregarded. Their flow should be determined, however, to make sure that it may be omitted from the calculations with safety.

The result of the computations just outlined should be checked by discharge measurements at the gorge and, where practicable, on the bar, by determining the area of cross section and measuring velocities. It must be remembered that the velocities of the tidal currents vary throughout the entire tidal cycle. To be of value in

computing the total tidal flow, velocities should be measured through several cycles in order that temporary aberrations may be eliminated and true values secured.

With the total flow through the entrance as a basis, the proper width of opening, the probable velocities and the resulting channel dimensions may be calculated. The trial and error method is clearly indicated, as width, velocity and depth are all interdependent. Velocities are increased by narrowing the entrance but decreased by enlargeing the channel. Increased velocities, however, result in greater scour and a consequent enlarged channel. The character of the material forming the bar enters into the problem in the extent to which it is erodible at different velocities and the slope at which it will stand on the sides of the channel after stability is esstablished.

It is impracticable and unnecessary to go deeply into the methods of computation in a work of this character. No unusual mathematical processes are involved. It is simply a matter of cut and try until a satisfactory conclusion is reached. The end in view should be a channel which will maintain itself with little change when once established. The ebb current velocities in the completed channel should be sufficient to scour out any material brought in by the flood tide or washed into the entrance by storms, but not great enough to effect any material erosion in the established channel under normal conditions. With some classes of materials and in certain situations, particularly where the tidal prism is relatively small, it may prove desirable to depend upon dredging to assist the currents in forming the channel in the first instance, the contraction merely providing for maintenance.

Preliminary measurements of tidal current velocities on the bar and in the gorge will prove of value in estimating the variation of velocities is of importance in computing the effect of the discharge of the tidal volume through the entrance. While there are considerable differences in details in different localities, a good rule of thumb is to assume that the maximum velocities occur at and immediately after mid tide and are just twice the mean velocities. It must be remembered that the cross section is less at mid tide than at the beginning of the ebb.

If the jetties are not built to the level of high tide for at least the greater part of their length, it is necessary to make allowance for the water which escapes from the channel by spilling over the top of the contracting works. Some authorities even insist that allowance should be made for the lack of water tightness of the structures. It is believed that this is an unnecessary refinement, introducing a cor-

rection in an amount far less than probable errors elsewhere in the calculation. The jetties will soon be made essentially water-tight by sand deposited in the interstices to at least mid tide level. The amount of water which can be lost under these circumstances can scarcely be of sufficient moment to affect the results.

A study of velocities, widths and depths, in channels within the harbor will often be of assistance in checking assumptions as to the erosive effects of the several velocities on the bar. The channel at the gorge is an especially good guide for use in verification of the final decision of entrance channel width and depth. There must be no attempt, however, to duplicate the dimensions of the gorge channel on the bar. The gorge channel is caused by the concentration of the ebb currents in the throat of the harbor. It is protected from wave action by the headlands at the entrance and by the bar. Frequently it is located at a bend in the channel and receives the benefit of the added scouring effect peculiar to such location. None of these favorable conditions exist in the bar channel. Consequently we cannot expect to secure as great a depth on the bar as in the gorge and there must be a correspondingly greater width.

Finally the width of entrance should be examined in the light of velocities to be expected when interior rivers are in flood. This can hardly be material except in the case of a rather small tidal basin into which flows a large river subject to great floods. In such case the river flow, being much greater than that taken into account in the originl calculations, might produce excessive velocities between the jetties. If the floods be of short duration this would not be objectionable, as an occasional flushing out of the channel would do good rather than harm. Prolonged floods might occasion serious damage, however, and must be taken into account.

Jety Trace. Having determined the location of the channel and the proper width of entrance, the next step is to settle upon the siting of the jetty structures themselves. Here we have considerable leeway and can take full advantage of any local peculiarities which lend themselves to economy of materials or methods. While a correct general location is essential, delicate refinements of trace are immaterial.

One fundamentl principle should be stressed. Where it is at all feasible, jetties converging toward the entrance from shore ends a considerable distance apart are to be preferred to parallel jetties. An exceptional to this rule is found at the mouths of rivers flowing directly to the sea, that is, without any expansion of their mouths into a tidal estuary. This case will be discussed later. Another possible exception is the harbor with a very narrow natural throat.

Even here, however, it will frequently prove advantageous to adopt the converging trace, thus forming an outer basing with the throat serving as a connecting channel to the inner harbor.

Often parallel jetties must be longer than the converging type to reach the critical point on the bar and they will usually involve the use of more material since they will almost invariably be sited in deeper water. Parallel jetties are also more subject to damage from racing currents. But the great objection to the parallel trace is the situation created in the inner harbor. Storm waves travel with practically undiminished amplitude through the deepened channel between parallel jetties and create most undesirable conditions at the inner end. Cases have arisen in practice where harbors have been seriously harmed through this cause alone. Here the deepened entrance is a detriment rather than an improvement.

The converging trace, on the other hand, has much to recommend it. Only the outer end is fixed by the location of the channel. The rest of the jetty may be sited wherever local conditions indicate, usually along the line of shoalest water so as to use the smallest possible amount of stone. The shape of the trace, is most favorable to the protection of the structures from damage by interior currents. Except at the outer end the main current will usually be some distance from the jetty. Usually sand will be deposited in the inner angles, giving added protection to the structure. Where the current does approach too near the jetty from any cause it is a simple matter to force it away and give protection to the main jetty by constructing short groins on the inner face. The increased distance between the jetties tends to enlarge the tidal basin, always a desirable point. The important feature of this enlargement is that it provides a stilling basin for the storm waves which drive in through the entrance. The elimination of this very objectionable accompaniment of the parallel jetties is worth a great deal, even though there were no other advantages in favor of the converging trace.

In siting the jetties a few general principles must be borne in mind. One of the basic requirements of a successful jetty project is that the littoral drift shall be arrested until the new channel has become firmly established. This indicates the desirability of so locating the jetties as to provide storage space for the drifting sand, with capacity to suffice for several years. The more sand storage that can be provided in reason the better. Particularly is this true of the windward side. The structures should be based on the shore at high-water mark or higher. The reason for this is evident on brief consideration. Near the windward shore end of the

bar there is usually a "swash channel," a shallow beach channel formed by the concentration of the flood tide as it enters the harbor. Not infrequently a similar channel is found on the leeward side as well. From what has been learned as to the causes and action of the littoral drift, it is evident that this swash channel will naturally receive much of the drifting sand. If it be not closed off effectively, the major object of sand storage will not be attained. The heavy sand movement through the swash channel and along the beach proper will pass beyond the jetty into the main channel with disasterous results. Nothing but a high tide jetty at this point will meet the demands of the situation.

Subject to the general principles just outlined, the detailed siting is largely a matter of judicious adaption to the local conditions, in an attempt to secure the maximum of results from a minimum of expenditure. It has been advocated by some writers on the subject that the extreme outer ends of the twin jetties should be made parallel to each other and to the channel axis for a short distance, the width between them being reduced. The theory of this construction is that the rigid confinement of the flowing water just before it is released into the sea acts in the same manner as a nozzle on a hose; the confined and properly directed current holds the channel to the predetermined line and prevents an early dissipation of the concentrated flow, so that sand carried in suspension will not be dropped so soon. This theory cannot be supported in its entirety. To secure a true nozzle action there must be too much contraction in this section of the channel, with the accompanying difficulties of excessive scour, undermining of the contracting structures and all of the ills attendent upon over-contraction. Without the excess contraction, this proposed construction merely embodies the normal twin-jetty theory. The suggested refinement in trace is probably unnecessary as we know that there is every reason for a channel once established in the proper direction and at the proper location to maintain itself. However, it may be advisable at times to adopt the parallel construction for the outer ends of the jetties but at the normal distance apart. The outside angles in the trace would provide some additional sand storage, there might be a tendency for the littoral currents to be deflected farther to sea, there would be a steadying effect upon the ebb currents and little danger of undermining the jetties if the parallel section be not unduly prolonged.

Whatever trace be adopted for the outer extremity, the location from the shore to the point where the jetty crosses the crest of the bar will be about the same. By far the greatest single item

of cost in jetty construction is rock. Every effort should be made to adopt the trace which will require the least rock for its completion, other things being equal. Obviously the shoaler the water in which the jetty is built the less rock will be required to bring it to grade. The general line of shoalest water from the entrance to the shore should, therefore, be investigated as a tentative location for the jetty. This line can rarely be adopted in its entirety for the final location but it forms an excellent control for further investigation. The general trace should be convex to the inside, usually consisting of relatively long tangents connected by flat curves. For ease in construction no more curvature than is absolutely essential should be permitted. No part of the trace should be concave to the inside for fear that some vagrant current might start scour which would be difficult to control. If the general line of shoalest water is unduly long, locations involving a shorter trace in somewhat deeper water should be investigated. Finally the site which meets all the fundamental requirements and calls for the least practicably amount of stone will be determined and adopted.

In this study of the best and most economical location of the jetties, care must be taken to resist the temptation to make major changes in the siting. Frequently, it will be found that a material saving can be made if the location and direction of the bar channel be changed. View such inspirations with suspicion. Remember that there were very sound reasons for the adopted siting of the channel. Inquire carefully into the manner in which a change will affect the utility of the channel for navigation and its ease of maintenance. It will usually be found that there are valid objections against adopting the modification which at first appears so attractive.

Length. Considerations of economy naturally indicate that the jetties should be made as short as is consistent with effective action. There is, however, little that the designer can do in this direction without jeapordizing the success of the project. It has been seen that the jetty is sited in such way as to require the smallest practicable amount of rock between the shore and the crest of the bar. The only ways, then, in which the length of the structure may be reduced are by limiting the extension beyond the bar crest and by leaving gaps near the shore end. The dangers inherent in the latter method have already been presented. This practice has been thoroughly discredited by experience.

Likewise the apparent saving made by failing to extend the outer end to the point it really should reach is false economy. The effect, and indeed the purpose, of concentrating the currrents by

jetties is to scour out and move seaward great quantities of sand. This sand movement begins shortly after the jetties have been started and increases as the construction is advanced. Since the currents are not well confined in the early stages of the work, much of this sand is dropped on the outer side of the bar, which is accordingly widened seaward. As the jetties are pushed farther out and the currents are better confined, a larger proportion of the sand is carried to deeper water well to sea. The accretions to the bar become less and less, while the obstruction offered by the advanced bar decreases. Eventually a point is reached where the current breaks entirely through the remaining thin section of bar. The channel has been established.

It might be assumed that the goal of the improvement has now been reached. Unfortunately this is far from the case. The initial channel break-through usually occurs when the end of the jetty is somewhere in the vicinity of the original crest of the bar. If construction is stopped at this point the channel will maintain itself for a time, possibly for some years, but before long the bar will form a new crest, blocking the entrance. The history of jetty improvement is full of instances where the initial break-through has been taken as a successful completion of the project and construction stopped, only to have the bar reappear across the channel farther out, necessitating extensive subsequent operations and a greatly increased final cost.

There can be no assurance of permanence, in fact it may be assumed that there will be no permanence for the improvement, unless the jetties are extended across the bar to at least the depth of water it is desired to maintain in the bar channel. Nothing short of this will answer. Necessarily the final extension in deeper water will be expensive. But an attempt at economy by omitting any part of this essential finishing touch is foredoomed to failure. Experience has shown again and again what the inevitable result will be. A short period when the channel gives entire satisfaction will be followed by a period of gradual deterioation during which the channel is used with increasing difficulty, hoping against hope that the former condition will return. Finally it is recognized that there is no hope and an extension is undertaken with more difficulty and heavier expense than if done in the first instance, to say nothing of the losses to shipping interests while the channel was in unserviceable condition. It is much like trying to complete a masonry arch with a weak and poorly fitted key stone. The arch may stand precariously for a time but when the full load comes on it the entire structure falls.

Let us now examine briefly the manner in which the jetty system of proper length will act. The heavy scouring has been going on for some time and is well on the way to its conclusion by the time the structures are completed. There is still work for the currents to do in shaping the channel but this constantly grows less as time goes on. The concentrated current now has power to carry its lessened load farther to sea where it is more widely distributed. No longer is there danger of the sand being dropped in quantities on the very face of the bar. The littoral currents are concentrated across the end of the jetties and assist in the distribution of the sand by tending to carry it away from the entrance. While the new channel is being formed and its regimine established, the littoral drift is stopped and stored behind the jetties, so that the channel current has a minimum of material to handle. By the time the drift begins to pass around the end of the jetties, the channel is so well established that the currents are able to sweep the sand away and prevent it from forming an obstruction. Eventually the combined action of the littoral currents and the ebb flow will doubtless bring about the formation of a shoal to the leeward of the channel outside the bar proper. The channel bears away from this, however, and it does not cause trouble. The improvement may be considered as essentially permanent. It is possible that in the distant future the sand carried to sea may form a new bar but this is a remote contingency that cannot be guarded against now. Deep water soundings taken off the mouth of the Columbia River fail to show any material shoaling in the direction of the channel (southwest) but heavy deposits well to the north and a shoal just north of the channel. This is exactly what our consideration of the subject would lead us to expect and conditions point toward a long-continued success for the improvement. It was not, however, until the south jetty had been pushed far beyond the point where the first channel through the bar was formed and a north jetty had been constructed that these favorable results were secured.

Elevation of Crest. The height to which jetties should be built has long been a subject of discussion. The jetty built to the level of low tide only, that raised to midtide, and again the one carried to full high tide elevation-each has had its advocates in the past. In the early days of jetty construction a number of low tide jetties were built. It was believed that, as the scour was on the bottom, control of the flow next the bottom was all that was necessary. To build the jetties any higher under such circumstances would be a waste of money. But in practice such low structures effected so little concentration of currents and offered such slight obstruction

to the littoral drift that they failed of their purpose where either of these ends was of any moment. Low tide jetties alongside a channel originally created by dredging would assist materially in maintenance or even do all the work needed, in locations where the sand movement was slight. In such case, however, the same thing could be done by dredging at a cost less than the carrying charges on the jetties. The low tide jetty has, therefore, practically faded out of the picture. It seems very doubtful that there would be such a combination of circumstances as to justify construction of this type in future.

Jetties built to the height of mid tide were logically the next step. One of the chief claims made in favor of low jetties is that the flood tides are admitted more readily, thus keeping the tidal prism at its full natural volume. This claim loses most of its weight in the light of the observed fact that tidal range is practically never reduced in an appreciable amount by any proper jetty system. On the grounds of economy, however, there is a very strong argument for keeping the elevation of the crest as low as is compatible with effective results. Due to the trapezoidal section necessarily given to jetties, any reduction in the height gives a marked saving in the amount of stone and thus in the cost of the structure. The velocities of the ebb currents being greatest at and immediately after mid tide, the heaviest scour will necessarily occur at that time. These strongest currents will be as well controlled by mid tide jetties as by the higher ones, while there will be a fairly complete control of the major flow throughout the entire ebb. On the other hand the channel currents during the latter part of the flood will be somewhat lessened due to the fact that part of the flow is admitted over the tops of the jetties.

While there are cogent reasons favoring mid tide jetties, there are also valid objections to them. They do not effect a full concentration of the ebb flow, nor do they give the desirable protection of the channel against the littoral drift. Under certain conditions it may not be necessary to attain these objectives. In such case the mid tide jetty would answer all requirement, but it is questionable if a dredging project would not be cheaper under any set of conditions wherein mid tide jetties would be fully effective. In the general case, a successful jetty project will require the complete development of all possible favorable factors. For this, nothing short of jetties carried to full high tide level will serve.

A compromise design, with high tide elevation for the inner part, reducing to the height of mid tide at the outer ends, has been adopted on some projects. Such a plan, with say the inner half at the

level of high tide, the outer quarter at mid tide and the intermediate section sloping from one level to the other, would offer an entirely satisfactory solution in most cases. The littoral drift would be adequately controlled. There would be a reasonably complete concentration of the ebb flow and perfect control of its more effective part. The trouble with this idea lies in the practical difficulties attendent upon building and holding a jetty on such lines. It must be remembered that most jetties are built in locations subject to heavy storm action and that the outer ends, sited in deep water, are exposed to violent attack by the waves. The rubble mound jetty, which experience has shown to be the most practicable structure for this purpose, is certain to be beaten down and its crest lowered to some extent under this attack. The difficulties and heavy expense of repairs to these structures are such that maintenance operations cannot be carried on regularly but must be allowed to go for several years, when the accumulated ravages of the waves are made good. A jetty built to the suggested theoretical variable crest elevation would certainly lose much of its effectiveness in a short time under normal conditions, due to this degradation of its outer portion. In practice it has been found that a jetty built well above elevation of high tide throughout its length will assume a fairly close approximation to the suggested profile within a very few years, except that its extreme outer end is very apt to be below low tide rather than above. In a peculiarly favored location, not subject to violent storms, and where, accordingly, degradation of the jetty structure might reasonably be discounted, it might be practicable to build along some such lines as those outlined. Normally, however, it is necessary to make the original design for a high tide jetty throughout. Even then it will be but a short time before the outer ends have subsided under the battering of the waves to an undesirable extent.

Cross Section. In the early days of jetty construction it was usual to build with a crest width of not to exceed 10 feet and frequently only 5 feet. Side slopes were made 1 on 1¼ and even as steep as 1 on 1. It soon developed that such structures would not answer the requirements when exposed to such wave action as was experienced at many points. As a result of long experience, it is now the concensus of opinion that no jetty should be built with a crest width less than 20 feet and side slopes steeper than 1 on 1½ or 1¼ at the very least. Even these dimensions are not sufficient except in favorable locations. Where the jetties will be exposed to heavy storms the crests should be 40 feet in width and the slopes 1

on 2 or flatter. In such locations it is impracticable to state the final slopes definitely as they will be flattened down and adjusted to the conditions of the sea.

Of course it is necessary to assume definite quantites for purposes of preliminary design and estimate. Moreover is is essential that the assumptions be close to the true figures or the estimates will be of little value. Jetty work runs into such large amounts that erroneous assumptions in the basic quantities may well result in totals far from the true final cost. Fortunately the designer is not quite so badly handicapped in arriving at close estimates as might appear. There are now so many jetties on our coasts that it will usually be possible to find one or more which are exposed to much the same seas as the one under investigation. A close study of all reasonably similar cases, including methods followed and difficulties experienced as well as the sections which have stood the test of time, will give a very good idea of the design which may properly be expected to fulfill the requirements. The adoption of a section which has proved satisfactory under similar conditions is much the best and safest plan.

There may still arise a few cases for which parallel conditions cannot be found. For such cases it is desirable to consider a few general principles. The determination of the proper cross section may be based to a great extent upon the method of construction that is to be followed. This in turn is dependent almost wholly upon the exposure of the site and the character of the seas. The latter factors, of course, are really the controlling ones, but, as they determine the construction methods, these make a convenient yardstick. The best jetties can be built from floating plant by methods outlined hereafter. Here the heavy facing stones and the topping can be placed by derrick and fitted closely together, forming a structure which offers the maximum of resistance to attack by the waves. But this type of construction is practicable only where the sea is comparatively smooth most of the time and storms of great severity are infrequent. Under these conditions a jetty may be built with a cross section as indicated above for favorable locations with a reasonable certainty that there will be little degradation during or after construction, except at the extreme outer end, where periodic repairs will always be needed.

If the trestle method of construction is used there can be little placing of the surface stones. The material will take a rough natural slope as it is dumped from the cars only to be flattened out and compacted by the action of the waves. As has been stated, the advance determination of the final slope is difficult in this case.

However, experience shows that it is entirely practicable to use a theoretical equivalent cross section which will give the necessary amount of stone for purposes of making estimates. As the jetties are built up, sand will begin to collect along the outer faces making possible marked economies in stone. An equivalent cross section with side slopes assumed at 1 on 2 to 2½ dependent upon the severity of the seas will give a very close approximation to the amount of stone that will be required, although the actual slopes in the upper portion of the structure will be flatter than either of these figures.

In any case it is necessary to estimate on a certain amount of scour below the existing bottom and some settlement of the base into the sand. These must be based upon conditions at the site and experience at similar places.

Stone. The character of the stone used in jetty construction is a matter of prime importance. Very frequently the constructor is limited in his choice by the nature of the country stone and the great expense of bringing other material of better quality from a distance. Where the native stone is markedly inferior, however, a considerable increase in cost to secure a satisfactory quality is not only justifiable but advisable. Jetty stone should be dense, hard and tough, resistant to abrasion and not subject to disintegration when exposed to air or sea water.

The importance of density is sometimes overlooked. The resistance of a stone to movement by the waves varies directly with its under-water weight and inversely with its exposed surface. Let us examine what this means by comparing two cubical blocks, each weighing one long ton of 2240 pounds, one of sandstone with a specific gravity of 2.2 and the other of gneise with a specific gravity of 2.7, calling the first A and the second B. The weight of A under salt water is 1197 pounds, while that of B is 1390 pounds. The surface area of A is 38.56 square feet, of B 33.64 square feet. Remembering now that the quotient of submerged weight divided by surface gives an index of stability, we find this quotient is 31.05 for A and 41.34 for B. Thus B has one third greater stability although the two blocks weigh exactly the same.

But density alone is not sufficient. It is essential that a considerable part of the stone be in large pieces. Even in the most favorable locations, the jetty will at times be subjected to heavy attack by the sea. To resist these attacks, the outer end, the exposed sides and the cap must be protected by massive stones. No class of stone which cannot be quarried to produce many blocks of large size and fairly regular shape is suitable. Some heavy

varieties of stone are quite brittle. In addition to the difficulty of quarrying such stone in proper sizes, this is a fatal defect where the trestle method of construction is used. The large pieces will be broken on being dumped from the cars and the jetty will be composed of materials to small to resist the action of the waves. Most varieties of stone which comply with these requirements of density and toughness will possess the other necessary characteristics.

While the importance of large pieces has been emphasized, it must not be assumed that it is desirable to have no smaller stones. The use of nothing but large blocks would, in fact, be objectionable, entirely apart from the cost, which would be prohibitive due to the waste at the quarry. A core of properly graduated stones of smaller size makes the jetty much tighter and more serviceable. So much depends upon the details of design and local conditions that no fixed rule can be laid down as to the best proportion of different sizes. A few generalities may be indicative, however.

It was formerly believed that it was necessary to use all sizes of stone down to spalls and chips in order to insure a sufficiently tight jetty. It has been found, however, that this is not the case. If no large holes be left through the jetty, through which the waves can dash with considerable velocity, the interstices in the structure will soon fill with sand and all requirements for tightness are met automatically. On the other hand it may be real economy to use the smaller pieces under some conditions. If run of the quarry stone is accepted, the price will frequently be materially less than if a minor limit of weight is set. It costs the quarryman money to get rid of the stone he cannot sell. Unless he can find some market for the waste under his jetty contract, the cost of its disposal must be included in the price of the stone for which he receives pay. If the jetty is to be built by dumping from barges in a reasonably quiet sea, the chips and spells can be handled easily and cheaply and can do no harm. Under such conditions study should be given to the economics which may result from taking quarry run for the work, remembering that the weight of the spalls must be paid for and that the reduced price must compensate for the increased weight. It is, of course, necessary to set a limit on the amount of spalls which will be accepted. It is customary to classify the jetty materials by weight and to specify the percentage of each class which must be supplied. In such a case as that cited, a possible percentage distribution might be—not to exceed 10 percent weighing less than 10 pounds, not to exceed 20 percent weighing less than 500 pounds and at least 40 percent weighing over 3 tons, at least one quarter of the last classification to weigh not less than 6 tons.

Where currents and seas are strong, spalls should not be accepted. They will wash out before they can be covered by heavier stone, whereupon they may form troublesome shoals if in appreciable quantity. The lower limit in weight for such condition should be 25 pounds or more. A possible percentage distribution of material by weight to fit an average case of this type might be—not over 25 percent weighing from 25 to 1000 pounds and at least 45 percent weighing over 5 tons, half of which must weigh at least 8 tons. The only major limit in weight should be the capacity of the plant handling the material. No stone is too heavy to put in a jetty. In certain cases on the North Pacific coast 100 pounds has been set as the minor limit of weight.

If no suitable natural stone is available within reason, it will be necessary to build large concrete blocks for use on the exterior of the jetty, limiting the employment of the native stone to foundation and core. The necessity for heavy blocks in the exposed locations cannot be urged too strongly. If nature will not supply what is needed at reasonable cost. Man must make up the deficiency. It is unnecessary to comment at length on methods or plant for this purpose. Standard practice for mass concrete is followed, the aim being large, dense units. There are some marked advantages in the use of such concrete blocks, as they can made just the size and shape desired and can be fitted together to produce a smoother surface than is possible with natural stone.

Jetties at River Mouths. As has been stated heretofore, the design of a jetty system for the improvement of the mouth of a river flowing directly into the sea without the interposition of a tidal estuary or extensive harbor presents a different problem from the one we have been considering. Here the tidal prism is insignificant. Th flow of the river itself is the agent upon which dependence must be placed to maintain the channel. But it is also the river which is the principal offender in causing channel deperioration. Such a case as that now under consideration usually arises in nature where a stream which is heavily charged with silt during at least a considerable part of the time flows into a body of water with small tidal fluctuation. A stream of this type builds up its own flood plain, which it steadily extends into the sea through accretions to its delta. The bar at the mouth and shoaling in the entrance channel are caused almost wholly by the deposit of river-borne sediment. This deposit is increased and expedited by the reaction between the river flow and the salt water which under-runs it, particularly in the lower stages. Littoral drift bears a relatively minor part in the problem.

Since the trouble is caused by sediment transported by the river and the flow of the same river must be depended upon for the removal of the sediment after deposit, it is obvious that the improvement should be aimed at so controlling the discharge of the stream as to prevent any deposit until a point is reached where it will do no harm. To accomplish this end, the construction of a jetty system which will, in effect, move the mouth of the river seaward of the bar is evidently indicated. The underlying principles on which previous projects of this character have been based were thus stated by Vernon-Harcourt years ago: "The success of the jetty system dealing with those outlets depends on the distance to which those artificial banks are prolonged, the steepness of the slope of the sea bottom in front, and the existence of cross currents to remove the sediment. If no cross currents exist, the bar merely re-forms further out, in proportion to the length of the jetties, and the jetties require to be gradually extended."

The first factor cited in the preceding quotation is susceptible of some modification, as length is not the sole criterion of the effectiveness of the jetties. There are other features of great importance in the design of a system at a river mouth. These have been condensed by Dr. E. L. Corthell into the following rules, which were quoted with approval by a board of officers of the Corps of Engineers convened in 1916 to consider the improvement of Southwest Pass at the mouth of the Mississippi: "First. There should be two parallel jetties (or training works) connected with the ends of the land or the shores.

Second. The effective distance between the jetties should be that of those sections of the river, or outlet, where the best channel exists by nature.

Third. Projection of the jetties into the sea into about the depth of water required in the new channel by navigation, and in a direction either straight or curved, to meet the predominant sea currents at as nearly a right angle as possible.

Fourth. The jetties should be built their entire length well above the surface of high tide, so as to utilize the whole flow and prevent the deposit of material brought by the waves in the channel.

Fifth. The sea bottom should be protected from scour in advance of the progressing jetties to prevent scour beyond them.

Sixth. It is *sine qua non* that the jetties be pushed to completion as rapidly as possible to prevent the re-formation of the bar in advance, as happened at the mouth of the Rhone and at other works, leading to extra cost and often to failure.

Seventh. In the case of jetties where the tides are of sufficient amplitude to greatly accelerate the velocity of the tidal current by the works, the jetties should maintain their parallelism landward until they join the river banks at a point where the river has the normal depth of the proposed channel. If this rule is not followed there is likely to be troublesome deposit in the area above the land ends of the jetties, made either from the sedimentary matters of the river itself or by material excavated out of the bar channel by the incoming flood-tide current.''

It is believed that there is no call for any elaboration or explanation of these principles, in general. Their underlying reasons should be apparent from what has gone before. It is desired, however, to discuss briefly two of the rule as enunciated. The seventh rule should be made more rigid to advocate essential parallelism of the jetties throughout, whatever be the amplitude of the tides. The converging type of jetties is not suited to the mouth of a silt-bearing stream. If the jetties be based on the shore at some distance from the mouth, there is created between them. What amounts to a stilling basin. The sudden enlargement at the mouth of the river cannot but result in a reduction of velocity. This will necessarily be accompanied by a deposit which must be removed by dredging, as there is no other force to act upon it.

It will frequently be impracticable to apply the third rule, relating to length and direction of the jetties. The objections to curved jetties have been brought out previously. Their employment is considered most undesirable in any jetty project. It will thus usually be necessary to make the axis of the jettied channel essentially a prolongation of the lowest stretch of the river. This line may not be at right angles to the littoral currents, though it will usually not be far from perpendicular.

As a rule the bar at the mouth of an alluvial stream is composed of finer and more readily movable material than the bar formed from sea sand. The bar itself is softer, with less power to support the weight of a jetty structure. In the improvement of Southwest Pass at the mouth of the Mississippi it was found to be impossible to build the jetties to the crest of the bar as contemplated. They had to be stopped about 2000 feet short of their projected length because the bottom as too soft to support even the foundation mattresses. In such a case a jetty reaching deep water beyond the crest of the bar is obviously out of the question. It is not impossible to bring about a satisfactory improvement, however. Auxiliary dredging beyond the ends of the jetties will provide a solution. The jetties should be pushed out well toward the crest of the bar and

a channel dredged from that point to deep water. The axis of the dredged channel should be pointed into the prevailing wind, not in prolongation of the jettied channel. In this way the storm waves will have no tendency to wash material from the banks of the cut into the channel. The littoral current will deflect the silt-bearing river discharge to leeward, where the bulk of the sediment will be deposited, well out of the channel. Experience shows that such a channel, once well established by dredging, will tend to maintain itself with a minimum of assistance. On the other hand, a channel dredged in prolongation of the jetties will silt up almost as rapidly as it can be excavated. It must be expected that, as the river is constantly bringing down more sediment, the bar will eventually build up to an extent which will require extension of the jetties. The suggested expedient will, however, provide a good channel for years when other methods are impracticable.

JETTY CONSTRUCTION

Methods. As has been stated previously, jetties are ordinarily constructed either by the use of barges and floating derricks or by dumping from a trestle. Neither method will be given more than a general description here. Where floating plant is used, the foundation course and the core are customarily built with bottom-dump scows, which are accurately spotted in position before their loads are dropped. The heavy outer facing and cap stones are placed by floating derricks, the individual blocks being fitted together as closely as possible, in order that the finished structure may present as smooth and tight a surface as may be practicable.

The trestle method was devised to meet the conditions of heavy and almost constant wave action on the North Pacific coast. It was discovered, as soon as the construction of jetties as started on this coast, that the methods employed elsewhere would not answer here. Lost time and damaged plant were much too common, as the days are few and far between in this section when there is not a strong sea running, with a heavy surf breaking on the bar. Since the trestle system was adopted, however, work can be carried on almost continuously, being interrupted only during the period of the heaviest winter storms.

In the normal use of this method an elevated double-track tramway is constructed on the axis of the proposed jetty. The standard tramway has two tracks of 3 feet gauge, 13 feet between centers, with an elevation of 25 to 30 feet above low water. The spacing of the tracks is determined by the dimensions of the under-carriage of

the revolving pile-driver, which was especially designed to meet the requirements of this work. The rock is carried out on the tramway by means of specially constructed flat cars, capable of being dumped to either side. The foundation course of the jetty, which also serves the purpose of protecting the bottom around the pile bents and preventing erosion, is formed by dumping stone outside of both tracks and between the two. The jetty core is dumped between the tracks. The heavy facing stone is, of course, dumped outboard on each side. It is evident that, due to the method of placing the stone, the jetty will be far from compact, particularly on the faces, where the large blocks, falling irregularly, leave extensive holes in the structure. Under the action of the sea, however, the mass is gradually beaten down and compacted until an entirely satisfactory jetty results. The settling and compacting process usually takes three or four years, during which period more stone must be added to keep the structure to grade. This is not as objectionable as might appear, since the completion of a jetty usually requires several years and much of the restoration work can be done while active construction is still under way.

Ordinarily the stone must be delivered by barge to a receiving wharf and there loaded onto the dump cars. Where it is practicable to secure delivery on standard gage flat cars, a variation in the standard tramway system is sometimes expeditious and economical. If conditions are such that a trestle capable of carrying a train of standard cars can be built and maintained at reasonble cost, the delay and expense of transferring the stone to the special cars can be avoided. The unloading of the material at the proper point in the jetty may be accomplished by any of the mechanical means ordinarily used for such work. One ingenious method was employed recently by a contractor at Long Beach, California. The open face to the bucket of one-yard caterpillar shovel was blocked off with a steel plate. The shovel, mounted on a flat car, was moved to the end of a string of cars as soon as they had been spotted on the trestle. It then proceeded to shove the stone off of the cars with its bucket, moving along the train until the entire load had been disposed of. The shovel was then left on the last car, which was detached from the rest, and was ready for the next trainload. The plan was very successful and is worthy of consideration wherever applicable. While the use of standard equipment on the trestle may be desirable where conditions are entirely suitable, it must be realized that it is hardly practicable in very deep water or in a site exposed to heavy seas. In such a case the ordinary method is to be preferred.

Foundation Mats. In the early days of jetty construction it was believed that a rubble mound structure could not be expected to stand on a sandy bottom unless extraordinary precuations were taken. It was thought that loose stone thrown directly on the bottom would be swallowed up in the sand. For this reason builders went to great trouble and expense to provide special foundations on which the jetty proper could rest. The foundation usually took the form of a mattress of brush, logs or fascines, weighted down and sunk in position with stone. In some exposed locations the operation of sinking the foundation mats in position was extremely difficult, calling for great care and skill. In time experience showed that the mats were not needed in most cases, a layer of small stone making a perfectly dependable base for the jetty. At the present time the use of foundation mats is the exception, unless the bottom is so soft that the weight of the structure must be distributed by some such means. Some recent jetty designs have included the use of log mats for the lower course in the more protected sections but for an entirely different reason. Here the idea was to save cost. It was found that logs could be put in more cheaply than stone and would be equally effective, due to the protected location, the absence of teredo and the fact that the logs would be permanently submerged.

Order of Work. In the normal case, where no foundation mat is used, the jetty is based on a course of the smallest class of stone contemplated by the specifications. We have seen that this may be anything from stones with a minimum weight of 100 pounds to chips and spalls, depending upon circumstances—chiefly exposure. A certain percentage of larger stones must be mixed with the foundation layer to hold it in place until it is protected by later construction. The amount of higher class stone to be incorperated into the foundation course must be determined for each site, as no general rule can be laid down. The kind of stone used, exposure of the site, frequently and intensity of storms during the working season and the like are the elements of the problem. Ordinarily more large stone will be required in the outer part of the foundation than near the shore.

As soon as the foundation course is well under way, work is started on the jetty core, using the medium sized stone and the remainder of the smaller grade. The core is protected on the outside with the largest stone as rapidly as possible, in order that it may not be beaten down by unseasonable storms. After the work is well started, it is thus carried on in three stages simultaneously.

Foundation, core and facing are all being advanced. In this way the most advantageous use can be made of rock as delivered and its proper distribution can be most easily effected.

The foundation course must be kept well in advance of the superstructure. In addition to forming the base on which the jetty is constructed, this course has an important secondary function—if, indeed, it be not primary. As the jetty is pushed out from the shore, the concentration of currents around its end induces a scour on the bottom. This scour must be controlled or the height of the jetty and the amount of rock required to build it to grade will be enormously increased. The low foundation course acts as an apron lessening the scour to a reasonable amount, though rarely stopping it entirely. The necessity for estimating scour in determining the cross section was pointed out above. The distance which the foundation should be kept in advance of other work varies with the conditions. It should probably never be less than 500 feet under the most favorable conditions, while 2000 feet has been found none too much in an exceptionally bad situation. If a trestle is used, the apron must extend to the last bent to prevent scour around the piles. Where practicable, the apron should be extended some distance beyond the toe of the side slope, particularly on the leeward side, to prevent scour from overfall of storm waves during construction. When the work is being done from a tramway, this is obviously impracticable. In such case all that can be done is to repair any scour of this nature by dumping in an excess of rock and thus filling up the hole.

Completion. The upper part of the jetty core is peculiarly susceptible to wave action. It consists largely of small and medium weight stones and thus has little inherent power to resist degradation. On the other hand it reaches an elevation where the waves act with great power. For this reason, it is essential that the heavy facing stones be put in place as soon as practicable after the core is in. Here we encounter one of the major differences between the two methods of jetty construction.

In the type of sea where the barge method is usually employed, the core is ordinarily safe from any material derangement until it has reached an elevation of 5 feet or less below low water. It can accordingly be built to full section and protected as convenient with the heay stone. The facing blocks are dropped by derrick and allowed to roll down the slope until the side is thoroughly protected. When the facing has been placed to about 5 feet below low water in this way, the core is gradually built up to its full elevation, the facing stones being placed at the same time. This upper

part of the facing is set with great care. The blocks are fitted together as closely as possible, making a smooth surface with a minimum of voids. The cap stones are placed with equal care, an effort being made to have the side blocks overlap the cap, so the sides of the latter will not be exposed to the full force of the waves. In this system the full jetty section is completed as work progresses, making a proper allowance for settlement and consolidation. Settlement will ordinarily not be great with a well laid facing, if the slope has been given a good, firm toe or if sand collects against it, as is normal. Some consolidation will result from the facing blocks gradually fitting more closely together, largely from abrasion of small projecting points which hold the blocks from intimate contact when first placed.

In the heavier seas, where the jetty is built from a tramway in this country, we find a very different state of affairs. Wave action is severe to depths of 12 to 20 feet below low water, depending largely on the shape of the bottom, which determines the manner in which the waves are tripped. For average conditions 15 feet is probably the critical depth. Up to that elevation a slope of 1 on $1\frac{1}{2}$ or even $1\frac{1}{4}$ can be expected, practically the natural slope. From that elevation to the top of the structure, the action of the waves will impose flatter slopes. Obviously the width of the jetty at this elevation is too great to permit stone to be dropped in place from the tramway. It is necessary to build the mound high in the middle and depend upon the waves to flatten it out. Under these conditions, the line between core and facing is not very clearly drawn, while completion to full section at one operation is entirely impracticable. Weather permitting, it is customary to build the core up to about low water, dumping as much heavy stone outside as may be practicable. If waves are running high more heavy blocks must be mixed with the core material in order to prevent it from being washed away. As soon as this first mound has been washed down by the waves, more material is dumped on top. This process is continued until finally the jetty has taken its final form. The cross section is really determined by the waves, it will be seen. During the time the jetty is being extended into the sea, it is a simple matter to add stone as needed to the portions that have been pounded down. But the end of the last season's work sees the outer end finally brought to grade with a fill of newly placed stone. It is time to lay off the construction crew and dismantle the plant. Thus restoration cannot be carried on so easily at this critical point. It is usual to meet this situation by building the outer portion of the jetty high and wide, putting in as much

stone as possible. This effort to supply in advance the later deficiencies which may arise is only partially successful. A better method, where practicable, is to keep a small force on maintenance for a year or so after work is completed.

Continuity of operations and rapid progress are primary requisites in jetty construction. The jetties should be pushed forward to their full length with all practicable speed in order to "beat the bar". We have seen that the natural tendency of a jetty system is to build the bar seaward with the sand scoured from the new channel. A certain amount of this bar growth in prolongation of the channel axis cannot be prevented. But if construction be sufficiently rapid, the bar will not have advanced very far before the concentration of the currents is great enough to carry the eroded material beyond its face, preventing its further growth. More than one jetty project has had its success long delayed and its cost greatly increased through a failure to heed this fundamental consideration. Before work is started both funds and plant should be available in quantities ample to insure both rapidity and continuity of construction. It will often be necessary to suspend operations during the stormy season, especially when nearing the outer end of the jetty. These necessary periods of suspension should be made as short as practicable. When construction is being done by tramway, it will frequently be possible to continue work on the inner part of the jetty, making good the degradation caused by the beating of the sea, even when no work can be done on the outer end.

The early success of the project is best insured by simultaneous work on both jetties, keeping the windward one somewhat the farther advanced. However, such procedure involves the use of practically twice the amount of plant that would be required if the jetties were built one at a time. The size of the project and the difficulties of the site must be taken into consideration in determining the justification for the extra plant cost. If conditions are favorable, the completion of one jetty before the other is started may promise full success without any serious complications. In such case, when all or most of the construction plant must be purchased especially for the job, duplication of plant would probably not be justified. Particularly is this the case if the tramway method is to be used, with its expensive speciallized plant. If the jetties are built successively, the windward one should be first, for reasons which have appeared heretofore. We have seen that a single windward jetty will frequently give entirely satisfactory results for some years under favorable conditions. This will give time for the lee jetty to be finished before deterioration has set in. Com-

plete and early success for the project must not be jeapordized, however, by false economy on plant. If successive construction seems of doubtful promise, sufficient plant expenditure to insure simultaneous work is clearly desirable.

Maintenance. No jetty structure can be so well built that it will withstand the attacks of the sea indefinitely. Sooner or later repairs and restoration must be undertaken. The means employed are similar to those used for original construction and need not be gone into in detail. Here again the jetty built in a location where floating plant can be utilized presents much the easier problem. It is no great task to move a floating derrick and a few barge loads of rock to the site. Under these conditions, damages can and should be repaired without material delay.

This is not the case when the tramway must be used. Trestles go to pieces rapidly under the combined attacks of the seas and marine borers, with which so many of our waters are infested. The rebuilding of a trestle is a laborious process, as the piles must be driven through the enrockment of the original jetty. For this reason repairs are postponed as long as possible and are only undertaken when the jetty degradation has reached a point where the structure no longer serves its purpose. Many years usually elapse before maintenance operations are started. The work then assumes much of the character and magnitude of new construction.

Mention should be made of the method of maintenance and restoration used at Humbolt Bay, California, as a similar plan might be found advantageous elsewhere. Here the jetties were originally constructed by the trestle method, being completed in 1899 with the crest elevation at high water. They had been beaten down to about the level of low water before maintenance was started in 1912. The old jetties had become well compacted, of course, and formed an excellent foundation for the new work. The new crest was carried to about 10 feet above mean high water. The stone for the new jetty superstructure was carefully placed and fitted solidly together, the outer face being given a smooth and regular slope. The work was done with a crane operating on a double track, 17 feet out to out. The crane had a capacity of 20 tons at 35 feet radius. The track was laid on ties set in an 18 inch concrete cap built on the crest of the constructed jetty. Work was carried on progressively from the shore toward the outer end. At the sea end of the crest there was constructed a jetty-head consisting of a monolithic reinforced concrete block weighing about 1,000 tons.

It sometimes becomes necessary to protect a jetty from being undermined by the scour of currents too near its base. This is ordinarily done by depositing an apron of rip-rap along the toe of the slope. One man stone will answer in any usual situation but heavier stone must be used occasionally in very strong currents. Where the distance between the jetties can stand the contraction, groins of stone may be used for this purpose. This method is particularly applicable with tramway construction.

JETTIES VERSUS DREDGING

Until about the first of the present century the creation and maintenance by dredging of a deep channel across an ocean bar subject to any great wave action was a formidable and costly task. With the plant then available for such work, frequent and prolonged delays were the rule, resulting in a high unit cost for the material removed. As a result there were few bar channel projects involving dredging where the amount of material to be excavated was very great. The development of the sea-going section hopper dredge by the Engineer Department has removed much of the former objection to dredging. Such work can now be done with marked efficiency and at surprising low costs even in difficult locations. Consequently it is necessary to give improvement by dredging very serious consideration whenever a bar improvement is under study. There can be no doubt that many of our jetty projects would never have been constructed had the hopper dredge been perfected at the time they were in contemplation.

There are certain inherent objections against a dredged channel across an ocean bar when compared with one protected by jetties. Jetties act as breakwaters and afford protection to shipping in the bar channel during all storms except those in line with the axis. More important, however, is the constant deterioration to which a dredged channel is subject. While the tidal currents will assist in maintaining the cut during favorable weather conditions, the concentration is not sufficiently great to overcome the forces of the sea much of the time. The littoral drift will tend to shift the location of the channel, while every storm will cause shoaling. In some localities, a single heavy storm will destroy a dredged channel and necessitate months of work before it can be restored. Obviously dredging alone will not answer under such conditions.

There are, however, many places where sand movement is not so extensive and disturbances of the sea bottom by storms of sufficient severity to cause serious shoaling not of such frequent occurance but that dredging may be made to serve. In such a case it is

not at all improbable that a channel created and maintained by dredging will prove more economical than one protected by jetties. Jetty construction is enormously expensive at best. It may be urged in it's favor that a jettied channel maintains itself without cost and is always available, while constant maintenance is required where reliance is placed on dredging and, even then, the dredge may at times be unable to keep ahead of the shoaling, with a consequent impaired channel depth. Where this latter conditions exists, the objection is indeed serious. Frequently, however, it is possible to establish enough overdepth during the dredging season so that shoaling will not have reduced the depth too much before work can be resumed. A great deal of dredging can be done with the interest on the first cost of a jetty system. It must be remembered, too, that the jetties themselves will require costly maintenance and restoration from time to time.

All of these considerations must be given careful study in determining the type of improvement that should be adopted. When it is decided that jetties are required, it is well to make one final comparison after the system has been designed and its cost estimated, to see what could be accomplished by dredging on a scale comparable to the carrying charges on the structures contemplated. Sometimes such final comparison may cause an entire change in the project recommended.

It must not be assumed from the preceding paragraphs that dredging is urged in lieu of jetties in all possible cases. On the contrary, it is unquestionable that jetties are the only solution in many situations. Jetty construction involves the expenditure of such large sumes, however, that the designer must be thoroughly assured that no less expensive plan will serve. Once satisfied that a jetty system is essential, go boldly ahead with a design which will surely be adequate. If the prospective benefits from the improvement are not sufficient to warrant the cost of such a design, the project should be recommended adversely. Any attempt to experiment with an inadequate project because the cost can be lessened is certain to result unfortunately. The history of such attempts has shown that the pressure of events will finally force further action. Piecemeal additions will result and the ultimate cost will be greater than if an adequate plan had been adopted in the first instance. The recommendation should be either for no project at all or for one that will fully answer the requirements. Much more money has been lost through excess costs of completion of projects initiated on too modest a scale than on those that were too comprehensive.